9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

Disordered quasi-2D semiconductor structures: percolation, non-coherent mesoscopics, and conductance quantization

B. A. Aronzon[1], D. A. Bakaushin[2], N. K. Chumakov[1], A. B. Davydov[1] and *A. S. Vedeneev*[2]

[1] RSC "Kurchatov Institute", Moscow, Russia

[2] Institute of Radioengineering & Electronics RAS, Fryazino, Moscow distr. Russia

The electron transport properties of disordered (or condensed) quasi-2D semiconductor structures (in our case, the disorder is caused by the Coulomb-like chaotic potential relief induced by a statistic ensemble of built-in charges) are of the interest due to the fundamental problems open up-to-now. The ones actually imply the basic understanding of the metal-to-insulator transition regularities affected by both the system dimension and the disorder parameters. As the next, they entail the practical interest to the "quantum" FET-like systems with the conductance determined by the value of e^2/h at reliable conditions, say at temperatures much exceeding the 4.2 K.

Characteristic peculiarities of the electron transport previously observed in the structures with the strong fluctuation potential [1–3] are discussed in the report.

The objects for our consideration were the FET-like structures (i.e. the GaAs-based HEMTs or MESFETs both with a bulk or a delta-doping and the sub-micron gate-length, the Si-MOS FETs, etc.) presently used as the nano-electronic active elements. As we have shown, the built-in charge (the ionized impurity with the concentration $\sim 10^{18}$ cm^{-3}, i.e. $>10^{12}$ cm^{-2} induces the fluctuation potential (FP), strong enough (up to ~100 meV) to change the electron transport properties of these structures even at temperatures $T \sim 300$ K.

Meanwhile, main experiments we have performed using the Si-MNOS (Si-SiO_2-Si_3N_4-Me) structures with the inversion n-channel as the model-object. The tunneling-thin SiO_2 layer (~3 nm) allows setting the built-in charge concentration (the negative charge on electron traps at the SiO_2–Si_3N_4 interface, i.e. the FP sources) in the frame of $10^{10}-10^{13}$ cm^{-2} by means of the electron injection from Si at strong electric-field (at the gate voltage $V_g > 30$ V). This way one can actually change the sample properties in a broad region by setting different built-in charge realization, which controls the energy and space scales of the FP.

The results under our consideration, thus obtained for the Si-MNOS structures [1–3], i.e. dependence of the Hall-effect and the conductance G vs. the gate voltage V_g and the temperature T (in the range 4.2–300 K) are as follows:

— the threshold behavior of the Hall-effect voltage (at the constant drain voltage, ~10 mV, and low magnetic fields, <1 T) vs V_g, where the threshold of the Hall-effect disappearance corresponds to the finite value of the quasi-2D channel conductivity, $\sim e^2/h$;

— observation of the quasi-2D channel electrical non-homogeneity effected by the V_g decreasing; estimation of the non-homogeneity space scale, L_c, to be up to ~10 mm or more, followed by the conclusion that practical FETs could naturally show both the percolation and the mesoscopic properties (we mean the non-coherent mesoscopics);

— observation of the plateau region on the conductance G vs V_g curves at the characteristic value of the $G \sim e^2/h$ just in the case of FETs with the gate length $L_g < L_c$; the plateau has been commonly observed regardless to the temperature (4.2–300 K), the built-in charge concentration ($10^{12}-10^{13}$ cm^{-2}), their nature (impurities, ions, or traps) and sign (regarding to the charge carriers in the quasi-2D channel, i.e. electrons or holes), the substrate material (Si or GaAs), the gate length (0.3 - 10 mm), and the gate length to the width relation (1/10–1/1000); the effect causes the dG/dV_g vs G maximum at the argument value $\sim e^2/h$;

— observation of the quasi-activation behavior of the G vs T dependence with different values of the pre-exponent, $\sim e^2/h$ at high temperatures and more then the order less at intermediate temperatures; observation of the power-like low, $G \propto \text{const} + T^2$, in the low-temperature region.

The experimental results are discussed in frames of the percolation theory taking into account the quantum behavior of the resistive elements (the latter controls the percolation cluster conductance, see [4]) and the macroscopic scale of electron puddles (the walls of the FP), both determine the micrometer-long correlation scale of the percolation cluster in our case.

Other word, as we assume, the gate voltage reducing (i.e. reducing of the FP electron screening) leads to the system transformation: initially (high gate voltage) quasi-2D system thus transformed into the percolation system. In the latter case, the electron transport is performed by transition of electrons from a wall (the electron puddle) to the neighboring one through the FP passes. Thus connected puddles form the percolation net, and this net properties are controlled by both the FP sources and electron screening.

So, the discussed transition to the percolating net should lead to disappearance of the Hall effect at some characteristic value of the structure conductivity. In our case, the conductance threshold value $\sim e^2/h$ obviously shows that we deal with the quantum-scale system regardless to their macroscopic scales.

So, considering the G vs V_g and T peculiarities in the short-gate FETs ($L_g < L_c$) assumes a situation when the electron transport is carried out along a number of percolation paths and is controlled for the each path by the most resistive element, the only one saddle-point constriction of the FP. In contrast to [4], we consider the transport through the constriction taking into account not a step-like but a smooth energy dependence of the tunneling probability determined by the saddle curvatures [5]. Using both the experimental data and results of our computer simulation (in frames of the Landauer–Buttiker formalism) we have estimated the energy parameters, $h\omega_x$ and $h\omega_y$, characterizing the saddle curvatures along the electron transport and in the perpendicular direction respectively. At $G \sim e^2/h$ the parameters have been found to be of the same order, $h\omega_x \sim h\omega_y \sim 100$ meV, in accordance with results of the FP simulation in frames of statistical model. The estimations show a possibility of the conductance quantization at relatively high temperatures, $T \ll h\omega_y/2$ [5].

The electron effective state density, N_{ss}, and dependence of the $h\omega_x$ vs the Fermi energy have been also analyzed. As we have found out, the state density doesn't have any noticeable energy dependence and $N_{ss} \sim 2m/ph^2$, while the parameter $h\omega_x$ rapidly drops from ~100 meV down to ~1 meV with the Fermi energy decreasing. The latter means that reducing of the FP screening leads to the saddle transformation into the narrow and long ballistic channel and thus determines the conductance behavior vs the gate voltage and temperature.

Acknowledgement

The work has been supported by the grants of the RFBR (No 98-02-16747, 99-02-16955) and Physics of Solid Nanostructures (No 97-1081, 99-1123).

References

[1] B. A. Aronzon, E. Z. Meilikhov, D. A. Bakaushin, A. S. Vedeneev and V. V. Rylkov, *JETP-Lett.* **66**, 668 (1997).
[2] B. A. Aronzon, D. A. Bakaushin, A. S. Vedeneev, V. V. Rylkov and V. E. Sizov, *Semiconductors* **31**, 1261 (1997).
[3] B. A. Aronzon, D. A. Bakaushin, A. S. Vedeneev, A. B. Davydov, E. Z. Meilikhov and N. K. Chumakov, *Semiconductors* **35**, 448 (2001).
[4] Y. Meir, *Phys. Rev. Lett.* **83**, 3506 (1999).
[5] M. Buttiker, *Phys. Rev. B* **41**, 7906 (1990).